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Fission Surface Power Technology Development Status

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Abstract

Power is a critical consideration in planning exploration of the surfaces of the Moon, Mars, and beyond. Nuclear power is an important option, especially for locations in the solar system where sunlight is limited in availability or intensity. NASA is maintaining the option for fission surface power for the Moon and Mars by developing and demonstrating technology for an affordable fission surface power system. Because affordability drove the determination of the system concept that this technology will make possible, low development and recurring costs result, while required safety standards are maintained. However, an affordable approach to fission surface power also provides the benefits of simplicity, robustness, and conservatism in design. This paper will illuminate the multiplicity of benefits to an affordable approach to fission surface power, and will describe how the foundation for these benefits is being developed and demonstrated in the Exploration Technology Development Program's Fission Surface Power Project.

Introduction

The Fission Surface Power Systems (FSPS) project was initiated in 2007 to develop system level technology that provides the option for fission surface power for the U.S. Space Exploration Policy. The goals, elements, and plans of the FSPS project have been explained in detail previously (Ref. 1); the project key goals are to:

- Develop an FSPS concept that meets surface power requirements at reasonable cost with added benefits over competitive options
- Establish a hardware-based technical foundation for FSPS design concepts and reduce risk
- Reduce the cost uncertainties for FSPS and establish greater credibility for flight system cost estimates
- Generate the key gate products that would allow Agency decision-makers to consider FSPS as a viable option to proceed to flight development

This paper examines the aspects of conservatism, robustness, and simplicity that result from, and are inherent in, an affordable approach to fission surface power. Initiation of the FSPS project was contingent on successful demonstration that a fission surface power system could be developed affordably. Key principles of an affordable approach included selection of component performance goals well within envelopes of existing experience and demonstrated capabilities where possible, avoidance of component technology development (especially in the reactor) to the extent practical, and selection of component and

system solutions with lower risk and complexity, even at the expense of higher mass. A preliminary FSP concept was assembled using these principles, and the cost of the development of this concept through first and second flight units was calculated using a detailed and comprehensive work breakdown structure. A cost (FY 2007 dollars) of \$1.4 billion for development and first flight unit, and \$215 million for a second unit (both prior to application of reserves) was the result of the joint NASA/DOE cost estimation exercise that was also reviewed by aerospace industry systems development companies. Since the study was completed, however, it has become increasingly apparent that the principles of affordability applied to space nuclear power system development produce a range of benefits to potential users beyond just cost minimization. These resultant characteristics of simplicity, robustness, and conservatism will be reviewed below.

An update of technology development activities to implement and demonstrate affordable fission surface power simplicity, robustness, and conservatism will also be provided. The FSPS project has recently advanced from early subscale component level technology demonstrations to the initiation of hardware development for a non-nuclear system level technology demonstration at 1/4 power and full scale in a relevant thermal-vacuum environment, called the FSP Technology Demonstration Unit (TDU). Test configurations and results of early subscale “Pathfinder” testing will be reviewed, illustrating how these Pathfinders have built confidence toward proceeding with TDU development. Status of TDU development activities and progress will be summarized.

Nomenclature

AFSPSS	Affordable Fission Surface Power System Study
ARPS	Advanced Radioisotope Power System
Cx	Constellation (NASA Vision for Space Exploration flight hardware development program)
DOE	Department of Energy
ETDP	Exploration Technology Development Program
FSP	Fission Surface Power
FSPS	Fission Surface Power System
FY	Fiscal Year
GPHS	General Purpose Heat Source
GRC	Glenn Research Center
HR	Heat Rejection
HRS	Heat Rejection System
HX	Heat Exchanger
I&C	Instrumentation and Controls
INL	Idaho National Laboratory
kg	kilogram
kW	kilowatts
kWe	kilowatts (electric)
kWt	kilowatts (thermal)
LaNL	Los Alamos National Laboratory
LaRC	Langley Research Center
m	meter
MSFC	Marshall Space Flight Center
MT	Metric Tons (1,000 kg)
NaK	Sodium/Potassium mixture
NASA	National Aeronautics and Space Administration
ORNL	Oak Ridge National Laboratory
PC	Power Conversion
PMAD	Power Management and Distribution
RDU	Radiator Demonstration Unit

rem	Roentgen Equivalent Man
Rx	Reactor
SNL	Sandia National Laboratory
TDU	Technology Demonstration Unit
TRL	Technology Readiness Level
yr	year

Benefits of an Affordable Approach to Fission Surface Power

The Affordable Fission Surface Power System Study (AFSPSS) completed in 2007 was a collaborative effort that included participation from NASA, DOE, and nuclear industry expert consultants, and review by industry. The study team identified strategies to achieve affordability that included:

- Modest requirements and operating conditions
- Selection of a well-established reactor concept
- Significant terrestrial and some space experience
- Large fabrication experience (low cost)
- Large operational database
- Reactor design for self regulation of perturbations with large margins
- Robust control system
- Extensive reliance on existing terrestrial and prior space nuclear power systems databases

Application of these strategies resulted in a FSP concept with the characteristics as shown in Table 1.

TABLE 1.—AFSPSS PRELIMINARY BASIS FOR AFFORDABILITY

Power level and design life	<ul style="list-style-type: none"> • 40 kWe, 5 to 8 years
Design approach	<ul style="list-style-type: none"> • 900 K liquid-metal cooled reactor with UO₂ fuel (terrestrial design basis), approximately 1 MWt thermal power level • Stirling power conversion with 850 K input, ~10 kWe/Stirling engine • 400 K water radiators (ISS-derived), <200 m² • 400 V transmission, 120 V bus (ISS-derived) for loads
Technology needs	<ul style="list-style-type: none"> • Liquid metal primary loop and Stirling hot-end interface • End-to-end system performance test (TDU) • Reactor criticality benchmarking tests
Launch and Startup	<ul style="list-style-type: none"> • Up to two units delivered on a single lunar lander • Reactor startup after installation and crew inspection
Mission and Environment	<ul style="list-style-type: none"> • One of several power sources for crew and equipment; backup power and crew availability provide contingency options • Technology and concept design extensible to Mars surface missions • Lunar day/night cycle, 50 to 350 K sink, accommodation of dust

The high energy density of nuclear power enabled a favorable trade on mass with risk and complexity, furthered also by the dominance of reactor and shielding mass with respect to the overall system mass.

The FSPS affordable design philosophy is founded in principles of conservatism, simplicity, and robustness.

Conservatism

Review of the historical performance and cost trends for terrestrial and space nuclear power system development efforts suggests that cost increases with performance. While mission requirements for lunar and Mars exploration are not yet final, review of prior planetary surface outpost planning efforts indicated that required power is likely to be relatively modest for a nuclear power system, on the order of 100 kWe. The high energy density of nuclear fuel allows a power system of this size to be small, on the order of 10 MT. Comparison to other lunar outpost element concepts showed that a FSPS would therefore be well within the range of payloads to be delivered to the outpost, and that the design of the FSPS need not be performance driven. Relaxation of performance as a design driver in favor of affordability presented an unconventional but useful set of design freedoms in defining a FSPS concept.

A cornerstone of the design architecture for an affordable FSPS was the choice of constraining the reactor coolant outlet temperature to less than 900 K. This represents a relatively low temperature (compare to 1375 K for the SP-100 reactor designed during the 1980s (Ref. 2)). Constraining the reactor operating temperature allows the use of stainless steel and other non-refractory materials for power system structure. In addition, there exists decades of experience with reactor operation at low temperature, assuring that the design and operation of the FSPS reactor will be in a well-understood regime, and that new technology development for the reactor system can be minimized.

Similar conservatism was applied in other conceptual definition choices. Throughout the FSPS conceptual design, component materials and fluids that have demonstrated compatibility with nuclear power applications were chosen to the maximum extent possible. Generous structural and performance margins were applied in structural design choices, as were large safety factors. Especially in the reactor module of the FSPS, the basis of the conceptual design for affordability was extensive terrestrial nuclear power system experience.

The FSPS concept is composed of the reactor module, the power conversion module, and the heat rejection module. Of these modules, new development of reactor module technology is expected to be the least affordable. For this reason, definition of an affordable FSPS concept included minimizing technology development within the reactor module. In addition to the choice of the low temperature, several other affordable features of the reactor module contribute to conservatism. Enriched uranium dioxide fuel, baselined for the FSPS, has been extensively used in terrestrial reactors. Planned fuel burn-up of less than 1 percent over 8 years alleviates concerns of fuel swelling due to build-up of fission product gases. NaK liquid metal reactor coolant has been used in fast spectrum reactors since the 1960s, and was the reactor coolant/heat transfer fluid used in the SNAP-10A reactor. Boron carbide shielding, selected for the portion of shielding to be launched with the reactor (supplemented with lunar regolith), also has been used extensively in terrestrial applications. These examples represent the continual emphasis on conservatism characterizing FSPS reactor module conceptual design.

The baseline power conversion system technology chosen for the FSPS concept is Stirling dynamic power conversion. Stirling power conversion underwent extensive development for space mission applications during the 1980s. The Space Power Demonstration Engine, consisting of two thermodynamically coupled 12.5 kWe Stirling engines, was built to demonstrate 25 kWe Stirling conversion for use with the SP-100 space power reactor. The SPDE demonstration, followed by separate testing of the separated individual Stirling engines, totaled nearly 2000 hr (Ref. 3). More recently, Stirling power conversion technology has been further developed for space science missions utilizing the plutonium 238 General Purpose Heat Source, as part of the NASA Science Mission Directorate's Advanced Radioisotope Power System (ARPS) program. Subkilowatt Stirling engines have been tested for over 10 years as part of this development (Ref. 4). Stirling engine technology development conservatism results from the approach of scaling the ARPS technology to the multi-kilowatt level while maximizing the use of ARPS thermodynamic design, structural design, and materials choices.

FSPS heat rejection technology conservatism is obtained primarily through the use of well-characterized fluids and materials. Water, pressurized to maintain the liquid state, is the fluid chosen for transfer of waste heat from the Stirling engines to the heat rejection system. Temperatures in the FSPS

heat rejection system will range from about 350 to 450 K. Decades of experience exists for the use of pressurized water in far more severe conditions in the radiation environment of terrestrial pressurized water reactors. Titanium heat pipes are the material choice for FSPS radiator heat dissipation, with water as the heat pipe working fluid. Titanium compatibility with water at temperatures is well established (Ref. 5); additionally, FSPS technology development includes future testing of titanium with water in a radiation environment to verify compatibility.

Simplicity

The FSPS concept that results from emphasis of affordability over performance (allowing mass to vary as needed) is characterized by simplicity as well as conservatism. Many aspects of simplicity, as will be seen below, are enabled by the FSPS technology characteristics and reflected in operational aspects of the FSPS, and therefore are not planned for validation during FSPS technology development. The basic aspects of FSPS simplicity that result from an affordable approach will be briefly reviewed.

While specific lunar or Mars outpost power and lifetime requirements have yet to be defined, the selection of modest system-level power goal of 40 kWe and lifetime goal of 8 years are fundamental to system simplicity. The modest power goal of 40 kWe reduces the thermal power of the reactor, simplifies the heat transport and thermal control needs, and minimizes the fission product that could contribute to material degradation. An 8-year life goal is key to this latter low demand on reactor fuel utilization. Both power and life allow the design of the reactor to be designed to operate at very moderate reactivity levels. This allows the design of the reactor with large margins against any possibility of uncommanded criticality (start-up). In addition, the lack of demand on reactor performance allows the flexibility to include, as part of the reactor characteristics, negative temperature reactivity feedback across the operating range of the reactor. This feature causes reactor reactivity to drop as temperature increases, resulting in a self-regulating characteristic of reactor operation that simplifies power system monitoring and control. Also because of its modest performance, the FSPS reactor responds slowly to changes, whether from control application or from unplanned transients. This contributes further to the simplicity of reactor monitoring and control. For details, see Poston, 2009 (Ref. 6).

Another FSPS feature that contributes to system simplicity resulting from modest power requirements is the implementation of parasitic load control. The FSPS concept includes a parasitic load resistor bank as part of the power management and distribution system. These resistors radiate as heat any power that is not being consumed by user loads, allowing near-continuous operation of the FSPS at the designed 40 kWe power output, with only minor changes resulting from the lunar day/night cycle.

An FSPS concept feature that will be demonstrated during FSPS technology development is modularity. Modular reactor, power conversion, and heat rejection modules allow simplified phased testing and buildup during technology development as well as during engineering development and assembly for launch. Another key byproduct of modularity is the ability to perform system-level testing with a non-nuclear reactor simulator. All of the features of the FSPS reactor that result from an affordable approach (extensive experience with reactor operation and dynamics, modest performance, slow response, negative temperature reactivity feedback, etc.) contribute to the ability to model the reactor dynamic behavior with a reactor simulator with large margins on simulation fidelity. This avoids the need to perform costly nuclear system-level testing during technology development, while still providing a system-level demonstration of technology readiness in an operational environment.

Robustness

FSPS design for affordability leads straightforwardly to system robustness through relaxation of demands on performance. A common definition of robustness refers to the characteristic of available margin on operating conditions, which as explained above is a direct result of design for affordability. However, FSPS design for affordability, combined with the high energy density of nuclear power, has the multiplicative result that the total system mass is relatively insensitive to changes in mass of modules

other than the reactor module itself. Put differently, the FSPS reactor and shield dominate the mass of the total system, to the order of approximately 60 percent. Redundant systems, additional structural mass, and de-rating of performance can be applied to reactor heat transport, power conversion, heat rejection, power management and distribution and system control hardware without major increases in total system mass.

Safety is the first and foremost benefit to which robustness can be applied as a design degree of freedom. While the engineering flight design of an FSPS awaits the selection of the option for fission surface power by exploration mission planners, maximizing safety for all mission phases through wide margins on safety-related design and operation will be an available capability of an affordable FSPS design.

High reliability and fault tolerance is also enabled by affordability-driven robustness. For example, consider a temporary loss of coolant flow to the FSPS reactor core resulting from a pump anomaly. Because of negative temperature reactivity feedback designed into the reactor, it would decrease its reactivity until the temperature adjusted to a new equilibrium level. Recovery from this condition would consist of restoring cooling via manipulation of liquid metal pumps and power conversion units until a nominal working configuration can be achieved. Once cooling flow is restored, the resulting reduction in temperature would cause the reactivity to increase, thus increasing the thermal output of the reactor. If necessary, reactor power could be adjusted through the rotation of control drums to provide a new optimum power level from the system. This scenario is provided as an example of how an affordable design provides capabilities that enable fault tolerance and recovery. Similar fault tolerance and recovery capability is available for conditions such as stuck reactor control drums, power conversion unit failure, radiator pump failure, radiator coolant loss, and electrical load loss.

Because light weight and high performance are not critical to an affordable design, FSPS designers will have the luxury of selecting near-term technology components and parts for FSPS subsystems. Additionally, available mass margins can be utilized to provide redundancy and fault tolerance. FSPS modules built for engineering models and flight hardware can be designed with inherent toughness to withstand rigorous testing, and the affordability of these robust modules will also allow multiple design cycles and hardware iterations.

Technology Development Progress

The FSPS technology development project initiation was contingent on demonstration of the affordability of a fission surface power system via a detailed, credible estimate of cost of an FSP concept that targeted affordability as its principle design objective. Similarly, it is anticipated that a prerequisite to acceptance of FSP as an option for exploration outpost is the demonstration of an FSP system model demonstration in an operational environment, NASA's definition of Technology Readiness Level 6 (Ref. 7). This demonstration is the primary goal of the FSPS project. An overview of the project, its objectives, elements, and schedule, can be found in Palac, 2009. Significant progress has been made during 2007 and 2008 in the "Pathfinder" portion of the FSPS project, which has consisted of subscale demonstrations of the readiness of FSPS components and subsystems for development into full-scale components of a system-level FSPS Technology Demonstration Unit (TDU). A summary of recent demonstrations is presented below, and is illustrated by Figure 1.

Reactor Simulator and Heat Transfer Loop

As described above, affordable FSP is a result of minimization of reactor system technology development. However, the technology of simulating an FSP reactor with electrical heating requires development and demonstration. Building on work started under the Prometheus space nuclear power and propulsion program earlier this decade, MSFC has undertaken development of reliable high energy density electrical heater bundles that can simulate nuclear reactor components. Recent accomplishments include the fabrication of a Thermal Simulator capable of producing over 2 kWt for over 100 hr. This Thermal Simulator represents one element of a 37-element core simulator for the TDU. It will be tested to validate its performance during the fall of 2009 (Ref. 8).

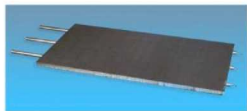
Pathfinder Subscale Demonstrations



Reactor Simulator



Liquid Metal Pump



Radiator Sub-panel



Heat Pipes



2 kWe Brayton Power Conversion



2 kWe Stirling Power Conversion



Irradiation Testing

Full Scale Component Demonstrations



Radiator Panel Demonstration



Reactor Simulator Heater Bundle Fabrication

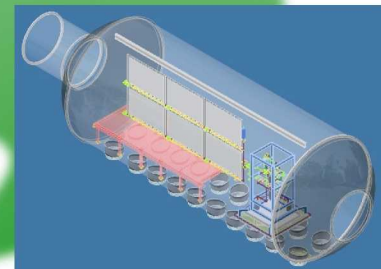


Power Conversion Design



Annular Linear Induction Pump

Full Scale System Demonstration



Technology Demonstration Unit Concept

Predecisional: For Planning Purposes Only

Figure 1.—Recent hardware successes form the basis for progression to system-level demonstration.

Transferring heat from the reactor simulator to the power conversion unit requires pumping of liquid metal NaK. In addition to its high performance as a heat transfer fluid, NaK also is amenable to pumping via interaction with an induced electromagnetic field. Electromagnetic pumps are typically less efficient and heavier than mechanical pumps, but have no moving parts, and therefore high reliability and simplicity. Electromagnetic pumps have been used in terrestrial liquid metal reactors, but none have been manufactured for over 15 years of the type suitable for an FSPS. Recently, fabrication of an electromagnetic Annular Linear Induction Pump (ALIP) was completed by Idaho National Laboratory and Pacific Northwest National Laboratory. It was practical to build an ALIP feasibility demonstration unit at full scale as an FSPS Pathfinder demonstration. The ALIP demonstration unit is designed to develop a pressure head of 58 to 68 kPa at a flow rate of approximately 4 kg/s. This pump will be installed in a liquid metal NaK test loop at MSFC in the fall of 2009 for performance testing (Ref. 9).

Power Conversion

Demonstration of Stirling engine readiness at multi-kilowatt electrical power levels was an important Pathfinder prerequisite to proceeding to full scale TDU power conversion unit design and fabrication. In addition, Stirling engine operation with heat supplied via liquid metal NaK had never been demonstrated prior to the FSPS Pathfinder demonstration. GRC worked with Sunpower, Inc., to modify a commercial

Stirling engine design to meet the requirements of a Pathfinder demonstration unit, and Sunpower, Inc. fabricated two 1 kWe Stirling engines. GRC added liquid metal NaK heat exchangers to the engines, which were subsequently installed and tested in MSFC's Primary Test Circuit laboratory. The NaK-heated Stirling pair demonstrated 2.4 kWe of power, with a more-uniform-than-expected circumferential temperature distribution in the NaK heat exchanger, indicating low structural stresses in this critical interface. This accomplishment provides confidence for proceeding with the detailed design and fabrication of a full scale 12 kWe Stirling power conversion unit for the FSPS TDU, to be initiated in the fall of 2009. Details of this demonstration, and all power conversion and heat rejection activities in the remainder of this summary, can be found in Mason, 2009 (Ref. 10).

For efficient transport of heat from the reactor to the power conversion system, the power conversion system must be located relatively close to the reactor. Stirling engines can thus be expected to be exposed to relatively high radiation doses during their operation. While the materials used in most of the Stirling engine structures and mechanisms are known to be tolerant of high radiation environments, some of the materials used in the linear alternator, and a few other areas of the Stirling engine, have less data available about their radiation tolerance. A recently completed Sandia National Laboratories irradiation test of a subscale Stirling alternator demonstrated operation of the alternator without degradation up to 20 times the expected gamma radiation dose for the life of an FSPS system. Material coupons representative of Stirling engine polymer adhesives, elastomers, tribological coatings, and wire insulation will also be irradiated in the Oak Ridge National Laboratory High Flux Isotope Reactor spent fuel pool in the fall of 2009.

Brayton power conversion is a viable back-up to Stirling power conversion for an FSPS. Though Brayton power conversion is less efficient than Stirling for the relatively low temperature heat from an affordable FSP reactor, Brayton engines have the benefit of low development risk, as there are commercial units currently available whose designs could be modified for an FSPS. A 2 kWe Brayton unit, original developed for the Solar Dynamic Flight Demonstration Project, was integrated with a MSFC-supplied Direct Drive Gas reactor simulator. Since Brayton power conversion uses gas as a working fluid in a closed loop for space power applications, the FSPS reactor would directly drive the Brayton closed loop by heating a gas, such as a helium/xenon mixture, which is then circulated to the Brayton power conversion unit. The demonstration was successfully completed in GRC's Vacuum Facility 6 in 2009, with the Brayton system producing 2 kWe at nominal operating conditions. The test also demonstrated the Reactor Simulator's capability to simulate reactivity control, successfully changing its heat output as a reactor would if commanded to change reactivity. During this testing, the Brayton unit responded as expected.

Heat Rejection

The FSPS heat rejection system must reject approximately 140 kWt of thermal power from the power conversion module at a temperature of 400 K or more. Titanium-water heat pipes embedded in composite radiators were selected as the most suitable technologies for these conditions, leveraging Prometheus Jupiter Icy Moons Orbiter mission studies. Over two years of heat pipe life demonstration, as well as three subscale composite radiator panels fabricated via contracted efforts, have provided FSPS needed data, courtesy of Prometheus Program initial technology investment. More recently, application of knowledge gained from these prior heat rejection demonstrations enabled the FSPS project to embark on development of a full scale "2nd Generation" Radiator Demonstration Unit (RDU). This RDU included a water manifold to deliver heat to the evaporator ends of the heat pipes, the heat pipes themselves, and the 1.7 m tall by 2.7 m wide composite radiator panels that radiate the heat distributed through the panel by the heat pipes. The RDU was tested over the summer of 2009 in the GRC Vacuum Facility 6, and it successfully demonstrated the rejection of 6 kWt of heat as designed under simulated lunar conditions. It supports the planned procurement of a 36 kWt TDU heat rejection system, planned to be initiated in the fall of 2010.

System Technology Demonstration Plans

With the completion of the FSPS Pathfinder feasibility demonstrations of FSPS components and subsystems, the foundation has been laid for progression to development of a full-scale, 1/4 power (12 kWe) TDU. A final design review of the TDU system will be conducted in the October 2009. Procurement of the Power Conversion Unit for the TDU has been initiated, with contract award times for the fall of 2009. Build-up of the Reactor Simulator, starting with the Thermal Simulator bundle fabrication, has begun. Elements of the primary loop will be added between now and spring of 2011, including a primary and secondary ALIP, and NaK piping and inventory management equipment. Testing of this assembled Reactor Simulator module will be conducted at MSFC to demonstrate capability with liquid metal NaK to supply heat to the power conversion unit. Once completed in 2012, the Reactor Simulator will be delivered to GRC for integration with the completed Power Conversion Unit. Testing of the combined Reactor Simulator/Power Conversion Unit, with facility water cooling in place of the Heat Rejection System, will be conducted into 2013. Development of the Heat Rejection System will begin in 2010 and be completed in 2013. The full TDU will be assembled in 2013, and completion of testing is anticipated in the fall of 2014.

Summary

In pursuing affordability of Fission Surface Power for its exploration mission, NASA and its partners have discovered that affordability leads to additional benefits that dramatically increase the conservatism, simplicity, and robustness of an FSPS. The benefits are only obtained, however, if the conceptual approach of an affordable FSPS is feasible. Recent Pathfinder demonstrations of FSPS components and subsystems have successfully demonstrated the fundamental FSPS approach to affordability is sound. This forms a solid basis for proceeding with the development of the system-level FSP Technology Demonstration Unit, which will establish the availability of Fission Surface Power as an option ready for development for NASA's Exploration mission needs.

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14. ABSTRACT Power is a critical consideration in planning exploration of the surfaces of the Moon, Mars, and beyond. Nuclear power is an important option, especially for locations in the solar system where sunlight is limited in availability or intensity. NASA is maintaining the option for fission surface power for the Moon and Mars by developing and demonstrating technology for an affordable fission surface power system. Because affordability drove the determination of the system concept that this technology will make possible, low development and recurring costs result, while required safety standards are maintained. However, an affordable approach to fission surface power also provides the benefits of simplicity, robustness, and conservatism in design. This paper will illuminate the multiplicity of benefits to an affordable approach to fission surface power, and will describe how the foundation for these benefits is being developed and demonstrated in the Exploration Technology Development Program's Fission Surface Power Project.					
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